

# Lunar Outgassing, Transient Phenomena and The Return to The Moon

## II: Predictions of Interaction between Outgassing and Regolith

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### ABSTRACT

In this second paper in the series, we consider the implications from Paper I on how gas leaking through the lunar surface might interact with the regolith, and in what respects this might affect or cause the appearance of optical Transient Lunar Phenomena (TLPs). We consider briefly a range of phenomena, but concentrate at the extremes of high and low gas flow rate, which might represent the more likely behaviors. Extremely fast i.e., explosive, expulsion of gas from the surface is investigated by examining the minimal amount of gas needed to displace a plug of regolith above a site of gaseous overpressure at the regolith's base. The area and timescale of this disturbance is consistent with observed TLPs. Furthermore there are several ways in which such an explosion might be expected to change the lunar surface appearance in a way consistent with many TLPs, including production of obscuration, brightening and color changes.

At the slow end of the volatile flow range, gas seeping from the interior is retained below the surface for extensive times due to the low diffusivity of regolith material. A special circumstance arises if the volatile flow contains water vapor, because water is uniquely capable of freezing as it passes from the base to the surface of the regolith. For a large TLP site, it is plausible to think of areas on the km<sup>2</sup> scale accumulating significant bodies of water ice. Furthermore, as the system evolves over geological time, the ice accumulation zone will evolve downwards into the regolith. Many possible reactions between the volatiles and regolith can act to decrease diffusivity in the regolith, depending on water and additional gases. Thus, it is plausible that the volatiles produce a barrier between the seepage source and vacuum, forcing the ice zone to expand outwards to larger areas.

These effects will influence some of the techniques we consider to further probe TLPs and other aspects of interactions between outgassing and the regolith. Paper III is devoted to describing these proposed techniques.

## 1. Introduction

From Paper I it is apparent that lunar outgassing and transient lunar phenomena (TLPs) are correlated, and we are thereby motivated to understand if this correlation is directly causal. It is a major purpose of this paper to explore quantitatively how outgassing might produce TLPs. Furthermore, it seems likely that outgassing activity is concentrated in several areas, which leads one to ask how outgassing might interact with and alter the regolith presumably overlying the source of gas. Some reviews of similar processes have been made, but few have been written since the integration of Apollo-era data e.g., Stern (1999), Mukherjee (1975), Friesen (1975) and none deal with the specific questions treated here.

It is evident from several experiments from the Apollo missions that gas is being produced in the vicinity of the Moon, even though these experiments differ on the total amount: 1) LACE (Lunar Atmosphere Composition Experiment on *Apollo 17*),  $\sim 0.1 \text{ g s}^{-1}$  over the entire lunar surface (Hodges et al. 1973, 1974); 2) SIDE (Suprathermal Ion Detector Experiment on *Apollo 12, 14, 15*),  $\sim 7 \text{ g s}^{-1}$  (Vondrak et al. 1974), or  $\sim 200 \text{ tonnes y}^{-1}$ ; 3) CCGE (Cold Cathode Gauge Experiment on *Apollo 12, 14, 15*),  $\lesssim 60 \text{ g s}^{-1}$  (Hodges et al. 1972). These measurements not only vary by more than two orders of magnitude but in assayed species and detection methods. The LACE result here applies only to neutral  $^{40}\text{Ar}$ ,  $^{36}\text{Ar}$  and  $^{20}\text{Ne}$ . The SIDE results all involve solely ions, and perhaps include a large contribution from molecular species (Vondrak et al. 1974). CCGE measures all neutral species, and cannot easily distinguish between them.

The LACE data provides clear evidence for episodic outgassing of  $^{40}\text{Ar}$  on timescales of a few months or less (Hodges & Hoffman 1975), but the results resolving this into faster timescales are more ambiguous. For now we consider the average rate. In the discussion below we will adopt the intermediate case, SIDE, for the total production of gas, of all species, ionized or neutral. The LACE is the only instrument to provide compositional ratios, which include additional, rarer components. We will use these ratios and in some cases normalize them against the SIDE totals.

Many of the following discussions are only marginally sensitive to the actual composition of the gas. For many components of molecular gas at the lunar surface, there is a possible contribution from cometary or meteoritic impacts, and a lesser amount from the solar wind. The influx of molecular gas from comets and meteorites is estimated usually in the range of tonnes or tens of tonnes  $\text{y}^{-1}$  over the lunar surface (see Anders et al. 1973, Morgan & Shemansky 1991). Cometary contributions may be sporadically greater (Thomas 1974). Except for  $\text{H}_2$ , solar wind interactions (Mukherjee 1975) provide only a small fraction of the molecular concentration seen at the surface (which are only marginally detected: Hoffman

& Hodges 1975). There is still uncertainty as to what fraction of this gas is endogenous. Current data do not succeed in resolving these questions, but we will return to consider them later in the context of gas seepage/regolith interactions.

## 2. Possible Modes of Outgassing/Regolith Interaction

One can easily picture several modes in which outgassing volatiles might interact with regolith on the way to the surface. These modes will come into play as one increases the flow rate of gas (and/or varies the regolith overburden), and we simply list them with mnemonic labels along with a description:

- 1) choke: complete blockage below the regolith, meaning that any chemistry or phase changes occur within the bedrock/megaregolith;
- 2) seep: gas is introduced slowly into the regolith, on essentially a molecule-by-molecule basis;
- 3) bubble: gas is introduced in macroscopic packets which stir or otherwise rearrange the regolith (such as “fluidization” e.g., Mills 1969);
- 4) gulp: gas is introduced in packets whose adiabatic expansion deposits kinetic energy into regolith and cools the gas, perhaps even freezing it onto regolith particles;
- 5) explode: gas is deposited in packets at base of the regolith leading to an explosion; and
- 6) jet: there is little or no entrained material and gas simply flows into the vacuum at the speed of sound.

While the intermediate processes might prove interesting, the extreme cases are probably more likely to be in effect and will receive more of our attention. In fact choking behavior might lead to explosions or jets, when the pressure blockage is released. Since these latter two processes involve primarily simple hydrodynamics (and eventually, newtonian ballistics), we will consider them first, and how they might relate to TLPs.

## 3. Explosive Outgassing

If outgassing occurs at a rate faster than simple percolation can sustain, and at a location where regolith obstructs its path to the surface, the accumulation of the gas will disrupt and cause bulk motion of the intervening regolith. The outgassing can lift the

regolith into a cloud in the temporary atmosphere caused by the event. The presence of such a cloud has the potential to increase the local albedo from the perspective of an outside observer due to increased reflectivity and possible Mie scattering of underlying regolith. Additionally, volatiles buried in the regolith layer might become entrained in this gas further changing the reflective properties of such a cloud.

Let us construct a simple model of explosive outgassing at the lunar surface. For such an event to occur, we assume a pocket of pressurized gas builds at the base of the regolith, where it was delivered by transport through the crust/megaregolith (presumably via channels/cracks or at least faster diffusion). Gas will accumulate at this depth until its internal pressure is sufficient to displace the overlying regolith mass, or some release of downward pressure occurs on a short timescale (impact, fluidization, puncturing a seal, seismic disturbance, etc.) We can estimate the amount of gas alone required to cause explosive outgassing by assuming that the internal energy of the buried gas is equal to the total energy necessary to raise the overlying cone of regolith to the surface. Of course, if there is any additional energy provided by the motion of delivery of the gas itself, this will reduce the overall gas mass necessary to displace the overlying regolith. This “minimal TLP” is the smallest outgassing event likely to produce potentially observable disruption at a new site, although re-eruption through thinned regolith will require less gas.

We can think of the outgassing event occurring in two parts. Initially, the gas bubble explodes upward pushing the overlying regolith with it until it reaches the level of the surface. Through this process the gas and regolith become mixed. At this point, the gas will expand and drag the regolith outward until it reaches a sufficiently small density to allow the gas to escape freely into the vacuum. In the “uncorking” phase, we use a simple analytical model, whereas for the expansion we numerically integrate averaged equations of motion in narrow timesteps to follow the acceleration of the entrained regolith in the expanding gas.

We discuss the depth of regolith further below; for this calculation we assume a typical depth of 15 m. Furthermore, we set the bulk density of the regolith at  $1.9 \text{ g cm}^{-3}$  (McKay et al. 1991), thereby setting the pressure at this depth at 0.45 atm. Because of the violent nature of an explosive outgassing, we assume that the cone of dust displaced will be  $45^\circ$  from vertical (comparable to the angle of repose for a disturbed slope of this depth: Carrier et al. 1991). The mass of overlying regolith defined by this cone is  $m = 7 \times 10^6 \text{ kg}$ .

By equating the energy necessary to lift the mass  $m$  of the regolith cone  $h = 15 \text{ m}$  ( $U = mgh$ , where  $g = 1.62 \text{ m s}^{-2}$ ) with the internal energy of the buried gas, we require 47,000 moles of gas. Much of this gas presumably consists of  $^4\text{He}$ ,  $^{36}\text{Ar}$  and  $^{40}\text{Ar}$  (see Paper I, op. cit.), so we assume a mean molecular mass for the model gas of  $\mu \approx 20 \text{ AMU}$ , hence

940 kg of gas is necessary to create an explosive outgassing event. The temperature at this depth is  $\sim 0^\circ\text{C}$  (see below), consequently implying an overall volume of gas of  $2300\text{ m}^3$  or a sphere 8.2 m in radius.

We assume that this mass of gas forces the regolith plug out of the surface and in the process the gas and regolith mix thoroughly in pressure, temperature, density and composition. After the plug is expelled, the gas continues to expand in a hemisphere centered on the plug until it can escape freely into the vacuum. Free escape should occur when the mean free path of a gas particle (without colliding with a dust particle) is on the order of the distance to the edge of the expanding hemisphere. The behavior of this cloud is legislated by the evolution of pressure acting on particles of varying cross-section. For the purposes of this calculation we idealize the particles as spheres and follow their evolution of motion in 512 logarithmically-spaced particle radius bins consistent with lunar maria samples (McKay et al. 1991).

Following the evolution of this cloud in small, constant timesteps, we monitor the typical trajectories of particles of different size. During this expansion, the gas does  $PdV$  work on the regolith, according to the ideal gas law and partitioned among the particles according to their cross section. We assume that the gas’s temperature stays in good thermal contact with the regolith, making it nearly isothermal. The total energy imparted to the dust is  $W = NRT \ln (V_{final}/V_{initial}) \approx 10^9\text{ J}$ , equivalent to about one-quarter ton of TNT. We let regolith particles fall from the distribution when the time since the initial explosion exceeds a particle’s ballistic “hang time” legislated by its kinetic energy. (We take the  $45^\circ$  case as typical.)

Because smaller particle sizes have larger cross-sectional area per unit mass and are thus more effectively accelerated outward, the cloud quickly differentiates with large particles dominating the central regions and small particles predominantly on the periphery. Figure 1 plots the hang times of different particles sizes versus time. The regolith particles larger than 100 micron (about 50% of the distribution by mass) remain aloft for only a few seconds, a large fraction falling in or near the explosion crater. Particles smaller than optical wavelengths stay aloft for many minutes.

We integrate the area of regolith particles from the top of the cloud to determine the optical thickness of different portions of the cloud. Figure 2 shows the size evolution of the optically thick cloud ( $\tau = 1$ ), which quickly expands to 5 km in diameter, where it remains fixed until the dust distribution is expended/collapses, about 1 minute after the explosion. At optical thickness  $\tau = 0.1$ , which might indicate the limit of any effect observable to the naked eye, the cloud expands quickly to 16 km diameter and remains there for about 100 s.

Experiments with agitation of lunar regolith (Garlick et al. 1972) show that the

reflectance of dust is nearly always increased under fluidization, typically by about 20% and often by about 50%, and similar results should be expected here. These increases in lunar surface brightness would be easily observable spread over the many square kilometers indicated by the model. Indeed, these areas and timescales would correspond to many reported TLPs at the less striking end of the distribution. Also, the cloud should cast a shadow that will be even more observable, blocking the solar flux from a comparable area. Furthermore, because the sub-micron particle sizes dominate the outer regions of the cloud (the outer 1 km of the optically thick cloud), it seems reasonable to expect Mie-scattering effects in this region with both blue and red clouds expected from different Sun-Earth-Moon orientations.

Some descriptions of TLPs, however, seem to indicate an increase in surface brightness even greater than any described here. In Appendix I, we discuss another mechanism which might both increase the surface brightness and change the cloud’s color, but drastic changes in these quantities seem beyond the model presented above.

The success of this model in reproducing the basic size and timescale of many TLP reports is encouraging, since it describes a basic process – outgassing forcing a puncture in the regolith layer. How often such an event should take place is unknown, not only due to uncertainty of the magnitude and distribution of endogenous gas flow to the surface, but also with how the regolith will react to a surface puncture. A new crater caused by explosive outgassing will cause the temperature structure of the regolith to adapt, with layers that are closer to the surface after the explosion cooling to accomodate the lesser amount of insulation by overlaying regolith. We will not attempt here to follow the next steps in the evolution of an outgassing “vent” in this way, but are inspired to understand how regolith, its temperature profile and gas interact, as in the next section.

#### 4. Seepage of Gas Through the Regolith

The question stands as to how fast the gas must accumulate in order to cause the explosive event in the previous section, rather than simple seepage. The escape of gas into the vacuum is regulated by the state of the regolith and is presumably largely diffusive.

Of special importance is the measured abundance of small particle sizes evident in the upper levels of the regolith, which pertains to depths  $\sim 15$  m (where bulk density is probably higher: Carrier et al. 1991). Assuming that particle distributions are self-similar in size distribution (constant porosity), for random-walk diffusion out of a volume element  $dV$ , the diffusion time step presumably scales with the particle size  $a$ , so the diffusion time  $t \propto a^{-1}$ . For particles of the same density, therefore, one should compute the diffusion time

by taking a  $a^{-1}$ -weighted average of particle sizes counted by mass.  $\langle a \rangle$ .

This moment of the distribution is the same required in the previous section. Published size distributions measured to sufficiently small sizes include again McKay et al. (1991) with  $\langle a \rangle = 24 \mu\text{m}$ , and supplemented on smaller sizes with *Apollo 11* sample 10084 (Basu & Molinaroli 2001), which reduces the average to about  $20 \mu\text{m}$ . This is an overestimate because a large fraction (34-63%) are agglutinates, which are groupings of much smaller particles, many having effective areas e.g.,  $e = A/4\pi r^2$ , with values of a few up to 8. (Here  $r$  is a mean radius from the center of mass to a surface element.) To a gas particle, the sub-particle size is more relevant than the agglutinate size, so the effective particle size of the entire sample might be considerably smaller, conceivably by a factor of a few. For the sake of discussion we adopt a random-walk step size  $l$  of  $10 \mu\text{m}$ .

At total gas pressure  $P_g = 0.45 \text{ atm}$  in Section 3, the mean free path is of order a few millimeters, much greater than  $l$ . This is in the Knudsen flow regime, where the flux of gas is  $J_k = 4K\mu(l/Z)P_g/\sqrt{2\pi kT\mu}$  (e.g., Schorghofer & Taylor 2007), where  $K$  is a factor of order unity,  $Z$  the depth below the surface (which we presume is  $\sim 15 \text{ m}$ ),  $\mu$  the mean atomic mass (20 AMU adopted above), and  $T$  the temperature ( $\sim 260\text{K}$ , see below). This gives  $J_k \approx 10^{-5} \text{ g cm}^{-2} \text{ s}^{-1}$  for these parameters, or  $\sim 20 \text{ g s}^{-1}$  over the spatial scale of an explosive event like the one considered above, several times larger than the SIDE outgassing rate. Local episodic outgassing might exceed the SIDE rate. To accumulate the amount of gas required to power one of these explosions requires about 1 d of lunar gas output at this rate. However, below, when we compare experimental simulation and Knudsen values, we suspect that the actual diffusivity might be significantly lower, so the required flow rate might also be lower (and the time to produce an event longer).

Were it not for phase changes of venting gas within the regolith, the composition of the gas might be a weak consideration in this paper (except for perhaps the molecular/atomic mass). Water plays a special role in this context (separate from others' concerns regarding resource exploitation or astrobiology), in that it is the only common substance encountering its triple point temperature in passing through the regolith, at least in many locations. This implies that even relatively small volatile flows containing water might tend to freeze in place and remain until after the flow stops. For water this occurs at  $0.01^\circ\text{C}$ , corresponding to  $0.006 \text{ atm}$  in pressure (the pressure dropping by a factor of 10 every  $\sim 25^\circ$ .)

Water is the only relevant substance to behave in this fashion, the next most common substances may be large hydrocarbons such as nonane or benzene, obviously not likely abundant endogenous effluents from the interior. Also  $\text{H}_2\text{SO}_4$  reaches its triple point, but changes radically with even modest concentrations of water. A similar statement can be made about  $\text{HNO}_3$ , which will not behave in its pure state, either. We consider only water's

phase-change effects in this paper.

We compare water seepage to experimental simulations, a reasonably close analogy being the sublimation of water ice buried up to 0.2 m below a medium of simulant JSC Mars-1 (Allen et al. 1998) operating at  $\sim 263^\circ\text{K}$  and 7 mbar (Chevrier et al. 2007), close to lunar regolith conditions in temperature and nearly at the water triple-point pressure (although we cannot be certain of the pressure environment due to other species, which probably dominate). Chevrier et al. find their experimental situation corresponds to the lifetime of 800 y for a 1 m ice layer, 1 m below the surface. The porosity of JSC Mars-1 is 44-54%, depending on compactification, versus  $\sim 49\%$  for lunar soil at the surface and  $\sim 40\%$  at a depth of 60 cm and slightly lower at large depths (Carrier et al. 1991). Lunar soil is slightly less diffusive even by solely this porosity measure. The mean size  $\langle a \rangle$  of JSC Mars-1 is  $93 \mu\text{m}$ ,  $\gtrsim 10$  times larger than that for *Apollo 17* and *11* regolith, accounting for agglutinates, so the corresponding timescale for lunar regolith material is, very approximately,  $\gtrsim 10$  ky (perhaps up to  $\sim 30$  ky). Other simulants are more analogous to lunar regolith, so that such experiments in the future might be made more relevant.

From the heat flow experiments at the *Apollo 15* and *17* ALSEP sites, (Langseth & Keihm 1977), we know that just below the surface, the stable regolith temperature is in the range of  $247 - 253\text{K}$  (dependent on latitude, of course), with gradients (below 1-2 m) of  $1.2 - 1.8 \text{ deg m}^{-1}$ , which extrapolates to  $0^\circ\text{C}$  at depths of  $13 - 16$  m below the surface. This is too deep to be affected significantly by variations in heating over monthly and lunar orbital precession timescales. This is an interesting depth, since in many areas the regolith is not quite this deep, as small as under a few meters near Lichtenberg (Schultz & Spudis 1983) and at the Surveyor 1 site near Flamsteed (Shoemaker & Morris 1970) to depths at Apollo sites (summarized by McKay et al. 1991) near the  $0^\circ\text{C}$  depths calculated above, up to probably 20 m or more in the highlands, and 40 m north of the south Pole-Aitken Basin (Bart & Melosh 2005). Presumably, the fractured zone supporting the regolith does not contain as many small particles useful for retaining water ice, as we detail below, but may also accumulate ice temporarily. A more recent heat flow analysis (Saito et al. 2007) would place the  $0^\circ\text{C}$  depth at least twice as far under the surface, increasing the lifetime of retained volatiles, but for now we proceed with a more conventional, shorter-lived analysis.

The current heat flow,  $\sim 3 \times 10^{-6} \text{ W cm}^{-2}$  (Langseth et al. 1972) would need to be  $\sim 10$  times higher in order to place the  $0^\circ\text{C}$  within about a meter of the surface and make ice formation more problematic. (Note, the  $\text{H}_2\text{O}$  triple-point pressure corresponds to the regolith overburden at 0.23 m, so ice at these shallow depths creates a dynamical instability.) In the case of the maria, this requires waiting until  $\sim 3$  Gy b.p., which is probably sufficient for the Moon globally (see Spohn et al. 2001). After this point the  $0^\circ\text{C}$  depth will recede into the regolith, while the regolith layer is also growing. Also, note



that at this time the average surface temperature was cooler by  $\sim 15^\circ\text{C}$  due to standard solar evolution (Gough 1981 – perhaps  $17^\circ$  lower in the highlands at 4 Gy b.p.). Since the thickness of regolith after 3 Gy b.p. grows at only about 1 m per Gy (Quaide & Oberbeck 1975), within the maria the  $0^\circ\text{C}$  depth sinks into bedrock/fractured zone. Whatever interaction and modification might be involved between the regolith and volatiles will proceed inwards, leaving previous epoch’s effects between the surface vacuum and the  $0^\circ\text{C}$  layer now at  $\sim 15$  m.

We should ask more generally of the fate of subsurface ice accumulation, perhaps from a time in the past when current flow measurements do not apply. Converting a loss rate for 1 m below the surface to 15 m would involve the depth ratio  $R$ . Experiments with varying depths of simulated regolith (Chevrier et al. 2007) show that the variation in lifetime indeed goes roughly as  $R^1$  as predicted (Farmer 1976), implying a 1 m ice slab lifetime at 15 m on the order of  $10^5$  to  $3 \times 10^5$  y. The vapor pressure for water ice drops a factor of 10 in passing from  $0^\circ\text{C}$  to current temperatures of about  $-23^\circ\text{C}$  just below the surface (also the naked-ice sublimation rate: Andreas 2007), which would indicate that  $\sim 90\%$  of water vapor tends to stick in overlying layers (without affecting the lifetime of the original layer, coincidentally). At the near-surface temperature at earlier times, 3-4 Gy b.p., this would be 98-99%. It is worth speculating that at these epochs volatile production was presumably higher, as would be ice production as soon as the temperature structure allowed, but this is difficult to estimate. At present, ice filling the interstices between regolith particles from 15 m to 1 m depth would amount to a surface density of  $\sim 7$  tonne  $\text{m}^{-2}$ , hence it would have a lifetime of order 1 My to a few My.

From above, there seem to be two evolution-dependent regimes that must be considered in volatile-regolith seepage interactions. The situation is entirely different when a gas source arises in pre-established regolith, rather than one in which volatiles have been seeping over geological time. In the former case, we can simply use Fick’s steady state diffusion equation  $\frac{\partial n}{\partial t} = -\kappa \nabla n$ , where spatial gradients are taken over 15 m, and scaling the JSC Mars-1 diffusivity of  $1.7 \text{ cm}^2 \text{ s}^{-1}$  to  $0.17 \text{ cm}^2 \text{ s}^{-1}$  for lunar regolith. Since the triple-point pressure corresponds to number density  $n = 2.4 \times 10^{17} \text{ cm}^{-3}$ ,  $\partial n / \partial t = 2.7 \times 10^{13} \text{ s}^{-1}$ , so that the regolith water vapor atmosphere needs replenishment daily. If now the total outgassing of  $7 \text{ g s}^{-1}$  includes  $0.1 \text{ g s}^{-1}$  of water, this rate can maintain a total volume of  $120 \text{ m}^3$  at the triple-point pressure. How much ice this atmosphere can maintain depends on geometrical details of the ice body, but it is probably of similar volume e.g., a few hundred  $\text{m}^2$  at 1 m thickness and typical porosity.

An alternative calculation is to consider the Knudsen flux given above, which at the  $\text{H}_2\text{O}$  triple-point conditions and a production rate of  $0.1 \text{ g s}^{-1}$  implies that a subsurface slab of ice at 15 m depth can be maintained with a topside surface area of  $60 \text{ m}^2$ . However, the

diffusivity from Chevrier et al. scaled to the same smaller particle size for lunar regolith versus simulant JSC Mars-1 is  $\sim 34$  times smaller than the Knudsen value, hence it should support an ice slab of about 2000 m<sup>2</sup> in area. There is a great deal of uncertainty in the input parameters, particularly the H<sub>2</sub>O input flux, but given this uncertainty it seems plausible that subsurface ice slabs of local geographical significance might have formed.

In the longterm case the volatiles may have interacted with the regolith over Gy, and due to the evolution of lunar heat flow versus regolith overburden, that interaction will tend to progress downward in a layer between the gas source and vacuum, thus potentially affecting the efficiency of volatile retention. This is primarily a question of whether minerals in solution precipitate in a layer filling the interstices between regolith particles, or other reactions accomplish a change in porosity.

There is little experimental work on the aqueous chemistry of lunar regolith (which will vary due to spatial inhomogeneity). Solution of lunar fines by water is greatly accelerated in the absence of other gases such as O<sub>2</sub> and N<sub>2</sub> (Gammage & Holmes 1975), and appears to proceed by etching the numerous damage tracks from solar-wind particles. This process acts to spread material from existing grains without reducing their size (which would otherwise tend to increase porosity). Liquid water is more effective than vapor, not surprisingly, and ice tends to establish a pseudo-liquid layer on its surface.

This is a complex chemical system that will probably not be understood without at least involving simulation experiments, but may involve prohibitive timescales. The major constituents are presumably silicates, which will migrate in solution only over geologic time. (On Earth, of order 30 My for quartz, 700 ky for orthoclase feldspar, KAlSi<sub>3</sub>O<sub>8</sub> and 80 ky for anorthite, CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>: Brantley 2004.) One might also expect the production of Ca(OH)<sub>2</sub>, plus perhaps Mg(OH)<sub>2</sub> and Fe(OH)<sub>2</sub>. It is not clear that Fe(OH)<sub>2</sub> would oxidize to more insoluble FeO(OH), but any free electrons would tend to encourage this. It seems that the result would be generally alkaline. Since feldspar appears to be a major component in some outgassing regions e.g., Aristarchus (McEwen et al. 1994), one should also anticipate the production of clays. This is not accounting for water reactions with other volatiles e.g., ammonia, which has been observed as a trace gas (Hoffman & Hodges 1975) perhaps in part endogenous to the Moon, and which near 0°C can dissolve in water at nearly unit mass ratio (also to make an alkaline solution). Carbon dioxide is a likely volatile constituent, and along with water can metamorphose olivine/pyroxene into Mg<sub>3</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>2</sub> i.e. talc, albeit slowly under these conditions; in general the presence of CO<sub>2</sub> and thereby H<sub>2</sub>CO<sub>3</sub> opens a wide range of possible reactions into carbonates. Likewise the presence of sulfur (or SO<sub>2</sub>) opens many possibilities e.g., CaSO<sub>4</sub>·H<sub>2</sub>O (gypsum), etc. Since we do not know the composition of outgassing volatiles in detail, we will probably need to inform simulation experiments with further remote sensing or in situ measurements.

The mechanical properties of this processed regolith is also difficult to predict. Some of these hydroxides expand, but a likely effect might be filling of the interstitial volume by material, which will raise its density and make it more homogeneous. It seems likely that any such void-filling will sharply reduce the rate of diffusion. Indeed many of the possible mineral combinations are cement-like, and experiments with water and anorthositic lunar chemical simulants have produced high quality cement without addition of other substances, except  $\text{SiO}_2$  (Horiguchi et al. 1996, 1998). Other substances that would be simple to produce are of very low hardness and not of high ductility. One needs to consider the effects of cracks or impacts into this medium; we speculate that vapor or solution flow would tend to deliver ice and/or solute to these areas and eventually act to isolate the system from the vacuum. This is probably not a dominant process, since even the overturn timescale to depths as shallow as 1 m is more than 1 Gy (Gault et al. 1974, Quaide & Oberbeck 1975)). Craters 75 m in diameter will permanently excavate to a 15 m depth (e.g., Collins 2001, and ignoring the effects of crack and breccia formation), and are formed at a rate of about  $1 \text{ Gy}^{-1} \text{ km}^{-2}$  (extending Neukum et al. [2001] with a Shoemaker number/size power-law index 2.9). The large flow into unmodified regolith discussed above might be disrupted by impacts roughly every 1 Gy. An exceptional case is Aristarchus, which may have radically affected any modifications resulting from outgassing in its vicinity, several hundred My ago.

The geologically long-lived, modified-regolith situation is complex, but we might hope to understand situations in which new outgassing vents have opened and have not affected their environment radically. We should consider a maximal outgassing site, presumably Aristarchus at about 60% of the total (Paper I), and a perhaps more typical site, at a few percent (say, 3%) of the total lunar flow rate. According to SIDE results, the total atmospheric production is 220 tonne/y.

How much of this is reasonable to consider as water? We see that lunar atmospheric water production might be suppressed by the regolith. On the Earth, water is the predominant volcanic juvenile outgassing component (Gerlach & Graeber 1985, Rubey 1964). While Earth is a radically different hydrological environment, we will see that the amount of water being discussed below is  $\lesssim 10^{-6}$  the compositional abundance on Earth. Furthermore, the current water content in the atmosphere is much less than what would affect hydration in lunar minerals (Mukherjee & Siscoe 1973 - although some lunar minerals seem to involve water in their formation environments: Williams & Gibson 1972, Saal et al. 2007, and perhaps Akhmanova et al. 1979).

The current best limit on water abundance is from the sunrise terminator abundances from LACE, which produces a number ratio of  $\text{H}_2\text{O}/^{40}\text{Ar}$  with a central value of 0.014 (with  $2\sigma$  limits of 0-0.04), which might indicate an actual  $\text{H}_2\text{O}/^{40}\text{Ar}$  outgassing rate ratio up to 5 times higher, converting spatial density to column density, given differing scale heights

(Hoffman & Hodges 1975). Adopting the LACE observation of  $^{40}\text{Ar}$  production of  $0.04 \text{ g s}^{-1}$ , corresponds to  $18 \text{ kg y}^{-1}$  for water (perhaps 5 times higher,  $90 \text{ kg y}^{-1}$ ). Adopting the SIDE rate of  $7 \text{ g s}^{-1}$  in the  $\sim 20\text{--}44$  AMU mass range, and assuming most of these are  $^{40}\text{Ar}$  (Vondrak, Freeman & Lindeman 1974: given the much lower solar wind contributions of other species in this range), this translates to  $15 \text{ tonne y}^{-1}$  in water, in which case most of which must be ionized upon escape into the vacuum. The disagreement between SIDE and LACE is a major source of uncertainty (perhaps due to the neutral/ionized component ambiguity). We also need to address what fraction of seeping water vapor might be trapped versus released in outgassing, which is now largely unknown.

In the case of initial eruption of an outgassing site, a prime site (presumably Aristarchus) might be expected to produce a 10 tonnes per year in water, hence, at a loss rate of a few  $\text{tonne m}^{-2} \text{ My}^{-1}$  as above is capable of maintaining a stable ice slab of order  $1 \text{ km}^2$  or less in area. For a minor site e.g., at 3% of the total lunar outgassing rate, this is a slab only of order 100 m or less in radius. At sizes this small or smaller, one must consider the diffusion as a two-dimensional rather than 1-D problem, in which case maintaining an equilibrium ice slab is even more problematic. Of course, this entire discussion depends on the spatial source function for the outgassing, which we have assumed is a point source but is currently unknown.

This result assumes unmodified regolith. Over geological time, in the case where the diffusion is sharply decreased by volatile/regolith chemistry, the area of the ice patch will increase until the boundary at the patch edge, where the regolith is unaltered by volatile interaction, corresponds to the patch area just derived e.g.,  $\sim 1 \text{ km}^2$ . The current outgassing rate at a prime site and taking the depth of the regolith,  $\sim 15 \text{ m}$ , for this margin, this implies a long-term equilibrium patch of order  $300 \text{ km}^2$ , or  $\sim 10^9$  tonne of ice at  $3 \text{ tonne m}^{-2}$ . At the current rate this mass might require several hundred My to accumulate, given all of these assumptions. Presumably the regolith at this margin might still become modified, and it is unlikely that outgassing has remained constant over the past 3 Gy, but we will not explore these possibilities further here.

Also recall that Aristarchus, along with Kepler, Copernicus and Tycho compose 60–70% of the robust events in Paper I, and all of these are major impact craters whose floors are likely to be covered with impact breccia and solidified impact melt, both likely to be largely impermeable except for surface cracks. Deeper cracks caused by these recent, major impacts may channel gas to these areas and may set up further regions relatively disconnected from the vacuum, hence they may be places of interest in terms of volatile collection.

The conclusion that we draw from the previous discussion is that it is not unreasonable to suspect that water ice might accumulate in large masses in the vicinity of major

outgassing sites, but that these would cover relatively small areas of the Moon, perhaps at the very most hundreds or thousands of  $\text{km}^2$ , not even 0.01% of the lunar surface (total of  $3.8 \times 10^7 \text{ km}^2$ ). In some way the current analysis evokes early hypotheses of subsurface ice (Gold 1962), but on a radically smaller scale. These sites are likely limited to a very small number of small areas where most of the outgassing occurs, not spread throughout the lunar surface.

The conclusion to be drawn, we reason, is that while subsurface water ice accumulation at outgassing sites is unlikely to be globally significant or even detectable in the mean properties of lunar materials, it may be a telltale tracer in particularly active areas to indicate the role of water as a minor constituent. With our current state of knowledge we might guess that the Aristarchus region is the first and perhaps only region worth investigating. Any accumulated ice will be covert, being unable to exist at the surface, but might conceivably be spread over areas under the surface that are nonetheless amenable to detection by remote sensing. It is unclear if our current samples of lunar materials are relevant to this assertion, in that none have been returned from the regions most suspected of outgassing, and the total amount of hydration produced by these effects is negligible when averaged over the lunar surface. In Paper III we outline methods which might be employed to resolve this issue.

## 5. Discussion and Conclusions

We are sensitive to the controversial nature of suggesting small but significant patches of subsurface water ice, given the history of the topic. In this series of papers, we take care to avoid “cargo cult science” – selection of data and interpretation to produce dramatic but subjectively biased conclusions that do not withstand further objective scrutiny (Feynman 1974). In Paper III we offer several straightforward and prompt tests of our conclusions and speculations which offer the prospect of settling many of these issues, although the intrinsically hidden nature of ice might make resolution difficult. We are operating in many cases in a regime where interesting observations have been made but the parameters e.g., the endogenous lunar molecular production (water vapor or otherwise), required to evaluate alternative models and interpretations are sufficiently uncertain so as to frustrate immediate progress. Despite the advances made primarily by Apollo-era research, we are still skirting the frontiers of ignorance.

A case in point is the interpretation of outbursts of molecular gas near the lunar surface. At least two instances of these were published with assertions of non-anthropogenic origin (Freeman et al. 1973, Hodges et al. 1973, 1974) and another has been discussed

without publication (Criswell & Freeman 1975). In the former two cases, discussions decades later (published and unpublished) have dismissed these case as anthropogenic despite the lack of new data (Freeman & Hills 1991, Hodges 1991). Initially the many SIDE outgassing events (Vondrak et al. 1974) were categorized neither as anthropogenic, endogenous or cometary/meteoroid impact-generated; these events’ nature have not been treated explicitly in publication. It would be useful for further lunar volatile analyses if a review of their probable origin were in hand; this is beyond the goal of this paper. Likewise an understanding of the large differences in fluxes seen by SIDE, LACE and the cold-cathode particle detectors would aid our analysis (see above).

Our results in this paper and in Paper I bear directly on the argument of Vondrak (1977) that TLPs as outgassing events are inconsistent with SIDE episodic outgassing results. The detection limits from ALSEP sites *Apollo 12*, *14* and *15* correspond to 16-71 tonne of gas per event at common TLP sites, particularly Aristarchus. (Vondrak states that given the uncertainties in gas transportation, these levels are uncertain at the level of an order of magnitude.) Our “minimal TLP event” described above is 20-100 times smaller than this, however, and still visible from Earth. It seems implausible that a spectrum of such events would never exceed the SIDE limit, but it is not so obvious such a large event would occur in the seven-year ALSEP operations interval.

The other impact of our work on the SIDE analysis is the placement of robust TLP sites relative to ALSEP sites. Most notably Alphonsus, adjacent to Apollo landings (particularly 14 and 12), drops from our list of persistent sites. We cannot be sure at present if Alphonsus undergoes dormant periods or simply is not a site of verifiable reports, but the SIDE upper limit of only 6.5 tonne per event for Alphonsus is no longer a meaningful constraint on TLPs.

The only persistent site of some statistical significance that corresponds to a sample return (170 g from Luna 24) is Mare Crisium, which is ambiguous in several ways: 1) the robust TLP report count for Mare Crisium is only zero to 6, depending on the robustness filter employed (Paper I); 2) the nature of this robust count is problematic given the extended nature of Mare Crisium as a feature, and 3) the sample returned from Mare Crisium is one case where the absence of water is ambiguous (Akhmanova et al. 1979), making volatile seepage in the vicinity harder to dismiss. In contrast, for Aristarchus the nearest sample return came from about 1100 km away (*Apollo 12*).

This is not to say that lunar samples have never produced clear evidence of endogenous water; picritic glass (Saal et al. 2007) fairly convincingly contains H<sub>2</sub>O at the level of 4-46 ppm ( $\pm 2$  ppm), in a way that points to magmatic origin. Previous studies of other lunar minerals e.g., apatite, have likely overlooked such contributions (McCubbin et al. 2007),

whereas particular samples occasionally have produced evidence of  $\text{H}_2\text{O}$  and other volatiles (Krähenbühl et al. 1973). The statement is often made in lunar geology that the Moon is “waterless,” “totally dry,” or the semantic equivalent. While it is clear on the basis of available evidence that such statements are true in spirit; formally or literally they are almost certainly incorrect. The question is the amount of uncertainty regarding the abundance of water within the Moon, either in terms of a tolerance or probability.

While this seems like a trivial point, it is not. While the temperature of the proto-Earth and progenitor impactor material in simulations grow to thousands of Kelvins, sufficient to drive off the great majority of all volatiles, these are not necessarily the only masses in the system. Either body might have been orbited by satellites containing appreciable volatiles, which would likely not be heated to a great degree and which would have a significant probability of being incorporated into the final Moon. Furthermore, there is recent discussion of significant water being delivered to Earth/Moon distances from the Sun in the minerals themselves (Lunine et al. 2007, Drake & Stimpfl 2007), and these remaining mineral-bound even at high temperatures up to 1000K (Stimpfl et al. 2007). The volume of surface water on Earth is at least  $1.4 \times 10^9 \text{ km}^3$ , so even if the specific abundance of lunar water is depleted at the 99.9999% level, one should still expect tens of billions of tonnes endogenous to the Moon, and it is unclear that later differentiation would eliminate this. This residual quantity of water would be more than sufficient to concern us with the regolith seepage processes outlined above.

Regardless of what one might believe on the controversial topics of endogenous water or the non-radiogenic composition of lunar outgassing, it seems clear that a simple model for the effects of gas from the interior of the Moon trying to penetrate the regolith might easily be consistent with the timescales and areas often quoted in TLP reports. There is a plausible mechanism to explain at least the magnitude of the phenomenon. Explaining every reported detail of TLPs is beyond the scope of this paper, and undoubtedly involves complex processes. While we deal with one of these in Appendix I, we think it probably best at this point to amass an objectively observed, relatively unbiased sample of lunar optical transients (Crotts et al. 2007). Providing the database from such a survey should be our goal given the much improved state of available technology.

## 6. Appendix: Coronal Discharge Luminescence Caused by Outgassing

In Section 3 we see that it is possible for dust particles to remain suspended for significant time intervals in a gas of number density  $10^{11}$  to  $10^{15} \text{ cm}^{-3}$  over scales of a

several tenths to several km; this seems a plausible situation for generation of significant electrostatic potentials. Considering that the regolith is composed of several predominant mineral compositions in various particle size ranges, under the action of suspension and acceleration by gas flow, dust particle charge segregation is possible.

For the following calculation we adopt a typical particle size of  $r = 10 \mu\text{m}$ , and a typical difference in work function  $\Delta W = 0.5 \text{ eV}$ . The actual value  $\Delta W$  for particles of even well-defined compositions is problematic due to various surface effects such as solar-wind/micrometeoritic weathering and exposed surface  $\text{Fe}^{2+}$  states. The following analysis suffices for two particles of different conducting composition; a similar result arises via triboelectric interaction of two different dielectrics (although the details are less well-understood). Disturbed dust is readily charged for long periods in the lunar surface environment (Stubbs, Vondrak & Farrell 2005).

Two particles will exchange charge upon contact until the equivalent of  $\pm 0.25\text{V}$  is maintained, which amounts to  $Q = CV = 4\pi\epsilon_0 rV = 2.8 \times 10^{-16} \text{ coulomb} = 1700 \text{ e}^-$ . When these two particles are drawn apart to a distance  $d \gg r$  their mutual capacitance becomes  $C_2 = 4\pi\epsilon_0 r^2/d$ . For  $d = 100 \text{ m}$ , assuming  $Q$  remains with the two particles, the voltage increases by 7 orders of magnitude! - which cannot be maintained. Note that Paschen's curve for coronal discharge goes through the minimal potential at 137V for argon, 156V for helium, at column densities  $N$  of  $3.2 \times 10^{16} \text{ cm}^{-2}$  and  $1.4 \times 10^{17} \text{ cm}^{-2}$ , respectively. In carefully controlled conditions, breakdown in He at potentials as low as 20V can be achieved (Compton, Lilly & Olmstead 1920). Nominally, however, Paschen's curves usually rise steeply for lesser column densities, and roughly proportional to  $N$  for larger column densities.

We take He and Ar as the primary outgassed components, since  $^{20}\text{Ne}$  is less well-established (Stern 1999) and likely of predominantly solar-wind origin (Hodges et al. 1974), and the abundance of molecular gas is also uncertain. The minimal-discharge column densities for molecules are similar to those for Ar and He, and minimum voltages are several times higher e.g., 420V at  $1.8 \times 10^{16} \text{ cm}^{-2}$  for  $\text{CO}_2$ ;  $\sim 430\text{V}$  for  $\text{NH}_3$ , 414V for  $\text{H}_2\text{S}$ , and 410V for  $\text{CH}_4$ , and similar  $N$  values for molecules e.g.,  $2.1 \times 10^{16} \text{ cm}^{-2}$ . These results are somewhat dependent of the structure and composition of the electrodes used in making these measurements.

The visual appearance of atomic emission of these gases in high voltage discharge tubes is well known, with He emitting a pink-orange glow (primarily from transitions at 4471.5Å, and 5875.7Å, plus 7065.2Å marginally visible to the naked eye: Reader & Corliss 1980), Ar a violet glow (from many lines 4159Å to 4880Å), and Ne, if present, producing intense red emission (with many lines 5852Å to 7032Å). It is plausible that TLP emission



reaching coronal discharge conditions would produce similar output spectra; the incidence of intense red emission in some TLP reports (Cameron 1978) argues for the presence of Ne; some other reports seem consistent with He and a smaller portion with Ar. Given the non-endogenous nature inferred for most Ne, however, we need to search for another gas in the case of very red events. The most common candidate molecules produce coronal emission that appears white ( $\text{CO}_2$ ) or red (water vapor - primarily  $\text{H}\alpha$ , which is produced in many hydrogen compounds;  $\text{CH}_4$  - Balmer lines plus CH bands at 390 and 431 nm).

In comparison, the events and their colors actually reported can be counted, although there is a significant range in outcomes depending on how one categorizes mixed colors and other factors. Following Paper I, we divide the sample at year 1956 (the latter composing 1/4 of the sample); before 1956: red - 11, blue (or blue-green) - 7, violet - 5, yellow - 4, red-yellow - 3, brown - 2, orange - 2; after 1955: red - 52, violet - 3, orange - 1. In the later reports, three red events also contain elements of violet/blue, plus one with orange, plus one with blue. Evidently red reports are common (out of the total sample of 894, not including the reports by Bartlett, which are largely blue), however, there is a statistically significant change after 1956, where about 1/5 of reports include red color, many associated with Aristarchus. This change is presumably due to a shift in the nature of observer reporting after 1955 rather than a change in the physics of the lunar events.

The initial gas density at the surface from a minimal TLP is of the order  $10^{18} \text{ cm}^{-3}$ , meaning that the optimal column for coronal discharge might conceivably be achieved on centimeter scales, whereas the initial outburst is over tens of meters. By the time a minimal TLP has expanded to 1 km radius, the density has dropped to  $\sim 10^{13} \text{ cm}^{-3}$ , so the Paschen minimal  $N$  holds over roughly the scale of the entire cloud, which is likely the most favorable condition for initiation of coronal discharge. If gas kinetic energy is converted to luminescence with, for instance, 2% efficiency, at this density this amounts to  $\sim 0.1 \text{ J m}^{-3}$ , or  $100 \text{ J m}^{-2}$ , compared to the Solar Constant ( $1366 \text{ W m}^{-2}$ , with a typical albedo of 7%, yielding  $100 \text{ W m}^{-2}$ ), so might be visible as a color shift for at least several seconds. This argues that a prolonged discharge luminescence effect, including color changes, would require a larger, sustained event (more than the minimal  $\sim 1$  tonne), since the lifetime of some colored TLPs reports is many minutes. It is not reasonable to think that a minimal TLP would sustain a coronal discharge over its entire  $\sim 45 \text{ s}$  lifetime sufficient to produce a visible color change.

Unless, in initiating the discharge, solar photoionization is important (which seems unnecessary), these phenomena should also be observable on the nightside surface, too, of which at least 20 are reported, usually a bright and/or variable spot, 8 at/near Aristarchus e.g., 1824 May 1, near Aristarchus “blinking light, 9th to 10th mag on dark side; 1881 February 3, near Aristarchus: “very bright, like an 8th mag star, pulsating;” 1789 May 29:

“flickering spot on east edge of Grimaldi,” etc. A rough calculation of Earthshine lunar surface brightness gives  $\sim 12$  to  $13$  mag arcsec $^{-2}$  in V, compared to  $3.4$  mag for full sunlight.

The kernel of many of these ideas has been suggested earlier (Mills 1970), and there is little doubt that luminous electrical discharges are generated in terrestrial volcanic dust clouds (Anderson et al. 1965, Thomas et al. 2007). In general reddish discharges may indicate  $H\alpha$  from dissociation of a number of molecular species, although is not the only possible explanation. Visual descriptions alone are probably not sufficient to settle this question, and the few spectra obtained of reported TLPs are sufficiently indistinct e.g., the Kozyrev (1958) spectrum, reported to show a transient spectrum of  $C_2$  Swan bands. Note that this observation was among those eliminated statistically by our robustness filters in Paper I. Kozyrev (1963) also reported transient  $H_2$  emission from Aristarchus (apparently absent Balmer lines).

Given the paucity of information from existing spectra and visual color observations, we advance in Paper III efficient means to obtain further spectra of TLP phenomena given a reliable imaging detection monitor, for which we are operating a prototype. Given the suggestion that red events might indicate one of several molecules, it is worth discussing what wavelength range might be best to observe for confirmation. Rather than relying on what might be a bright  $H\alpha$  line, plus faint optical lines and bands required to distinguish molecules e.g.,  $CH_4$  versus  $H_2O$  versus  $NH_3$ , we note that vibrational rotational bands for these (and other molecules) are brighter and more discriminatory in the near-infrared. K-band spectroscopy is likely to produce bright, distinctive features for these and many other molecular candidates, even if only  $H\alpha$  might be the only optical transition readily detected. This is discussed further in Paper III.

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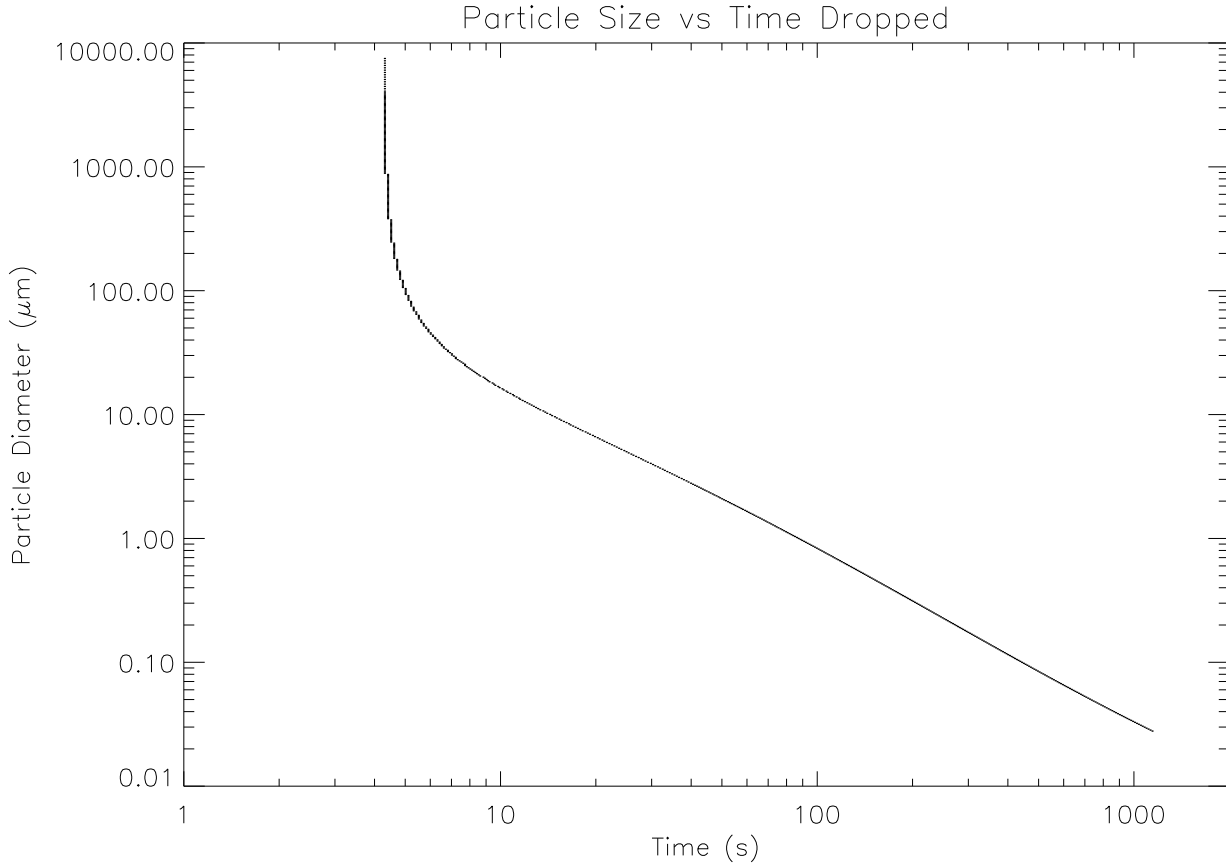


Fig. 1.— The time required for a typical regolith particle of the diameter shown to fall out of the expanding cloud back to the lunar surface. Particles larger than about 100 micron (about 50% by mass) rain immediately to the ground, barely exiting the initial crater, whereas particles smaller than optical wavelength remain aloft for at least several minutes.

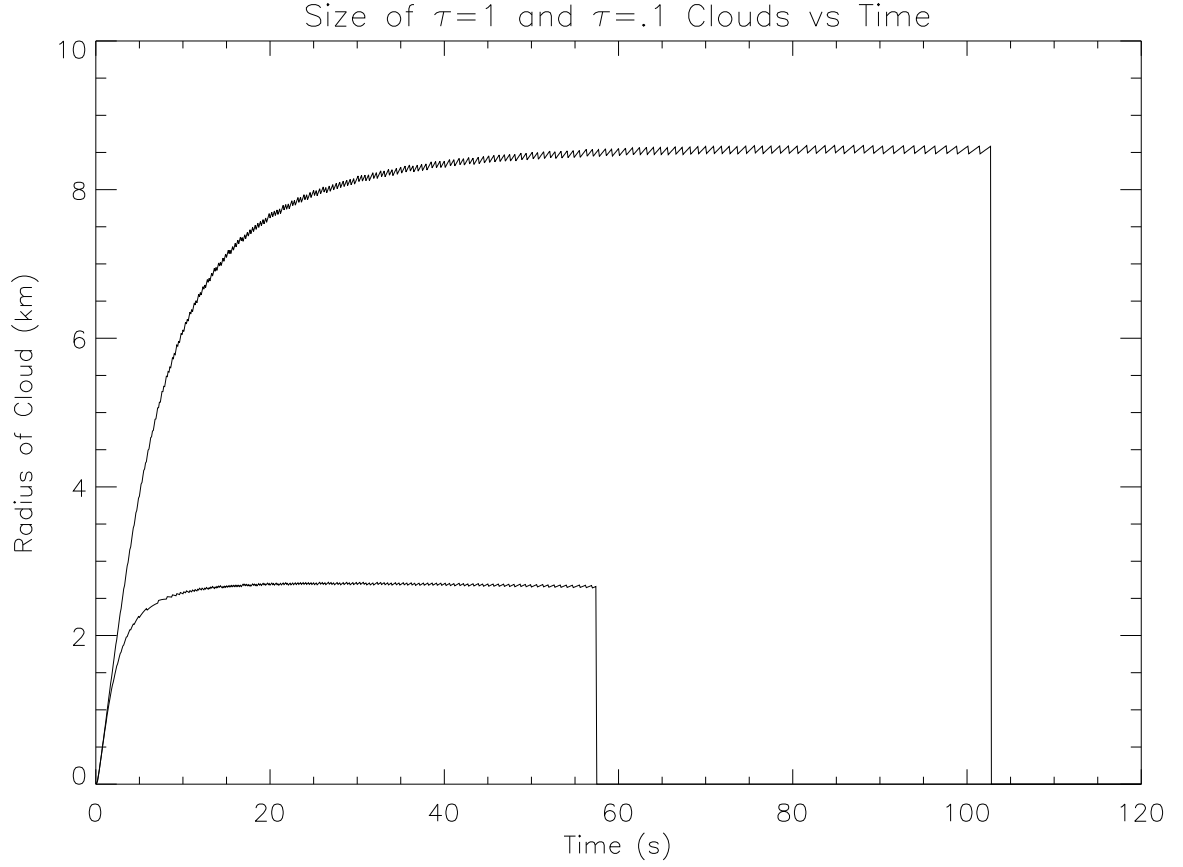


Fig. 2.— the time evolution of appearance in optical depth of the “minimal TLP” explosion, with the bottom trace showing the radius as a function of time of the optical depth unity surface of the dust cloud, and the top trace showing the optical depth  $\tau = 0.1$ , indicating the largest scale over which an optical disturbance might be readily visible.